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FINAL REPORT
TMC-NASA COLLABORATIVE RESEARCH PROJECT
PREDICTING BONE MECHANICAL PROPERTIES OF CANCELLOUS BONE BONE FROM DXA, MRI, AND FRACTAL DIMENSIONAL MEASUREMENTS

By

Timothy P. Harrigan, Catherine G. Ambrose, Department of Orthopedic Surgery, UT Medical School at Houston

Harry A. Hogan, Department of Mechanical Engineering, Texas A&M University

Linda Shackleford, Laurie Webster, Space Biomedical Research Institute, NASA Johnson Space Center

Adrian LeBlanc, Chen Lin, Harlan Evans, Department of Radiology, Baylor College of Medicine

SUMMARY

This project was aimed at making predictions of bone mechanical properties from non-invasive DXA and MRI measurements. Given the bone mechanical properties, stress calculations can be made to compare normal bone stresses to the stresses developed in exercise countermeasures against bone loss during space flight. These calculations in turn will be used to assess whether mechanical factors can explain bone loss in space.

In this study we assessed the use of T2* MRI imaging, DXA, and fractal dimensional analysis to predict strength and stiffness in cancellous bone.

INTRODUCTION

Bone is a well-known example of a tissue which adapts to mechanical stress, and it is well-established that bone density decreases during space flight due to the lower loads which are encountered there. The decrease in bone mass in the skeleton during space flight is a worrisome effect for astronauts, but it is also a valuable opportunity to assess the role of loading on bone physiology in otherwise very healthy individuals.

Some general observations indicate that the low load in space flight explains why astronauts lose bone, but the mechanisms are not clear. Bone loss in space flight is reported to be higher in bones which are normally loaded more heavily than others. For example, the calcaneus and the spine lose relatively more mass than the skull or the ribs. Thus the bones which are normally loaded heavily might react to a lack of loading more than those which are normally loaded lightly. However, the amount of bone lost is less than would be expected, given the close correlation between bone architecture and stress in some classical demonstrations of bone adaptation.

Based on the knowledge of stress-related bone remodeling, exercise countermeasures to bone loss in space flight are usually used to try to avoid bone loss, and they involve substantial exercise regimens. The overall goal of this line of research is to understand what sort of loads are best to use for exercise countermeasures, or whether non-mechanical treatments are adequate to ward off bone loss in space flight.

This study is focussed on providing material property data which is needed for mechanical stress calculations, which will then show how effective certain exercise countermeasures should be to keep from losing bone mass. This work will also be useful in studying many metabolic conditions which involve bone loss, such as osteoporosis.

METHODS: In preliminary experiments, we had seen that fresh-frozen human material , even when frozen en bloc within a limb segment, developed gas-phase voids which did not re-hydrate upon re-thawing These voids produced unacceptable MRI artifacts. Therefore, fresh unfrozen equine radius bones were obtained from animals euthanized for non-musculoskeletal conditions. The bones were cut in half and axial MRI scans were made of a 3cm region of the distal metaphysis, A Siemens 1.5T MRI scanner was used with a multi-gradient echo technique. Nine transverse images were made with a 3mm slice thickness, 160 mm field of vew, and a 64x64 matrix. The recovery time (TR) as 400 msec and echo times (TE) were 5, 10, 15, 20, and 25 msec. t2* was determined by fitting an exponential function to the TE pixel intensities. From each bone three slabs approximately 1 cm thick were cut and radiographs of the slabs were taken to plan the specimen locations. DXA measurements were used to determine bone mineral density (BMD) on these slabs as well.

Mechanical test specimens were cut in register with the MRI and DXA regions of interest. A series of cubes roughly 1 cm square were cut from each slab using an Isomet diamond saw. The cubes were weighed, measured, and frozen until thawed for mechanical testing. Elastic modulus and ulktimate strength were dermined using methods similar to Goulet et al (1994) and Keller (1994) Non-destructive loading was used in the superior/inferior (S/I), anterior/aosterior (A/P) and medial/lateral (M/L) directions Cyclic loading from 0 to 1% strain was applied at a strain rate of 1%./sec for 11 cycles, and the linear portion of the 11th cycle was used to calculate elastic modulus. The order of testing direction was randomly assigned, and the last loading cycle of the last direction for each specimen was taken to failure. Elastic modului and strength for each specimen were calculated using standard methods. Wet denaity and Bone mineral density

Linear least-square correlations were performed using wet bone density, BMD, t2*, and 1/t2* as independent variables, and using elastic modulus and ultimate strength in the three anatomic directions as dependent variables. Correlation coefficients (r and r^2) were compared to assess the relative ability to predict elastic modulus and strength in each anatomic dorection.

RESULTS: All correlations had p values less than 5% and the correlations with the best r values were thise which predict strength and elastic modulus from BMD measurements. In this study, the correlations which predict M/L properties were generally better than those which predict A/P properties, which were in turn generally better than those which predict S/I properties. Table 1 shows the summary data for independent and dependent variables.

TABLE 1

variable	Mean (SD)	N
S/I Strength	14.02(5.87) MPa	25
A/P Strength	4.86(2.44) MPa	27
M/L Strength	4.13(2.06) MPa	28
S/I Modulus	849.2(506.5) MPa	80
A/P Modulus	355.7(198.5) MPa	81
M/L Modulus	251.2(185.2) MPa	79
Wet Density	1.05 (0.06) g/cc	83
BMD	0.262(0.068)g/cm^2	83
T2*	14.22(2.93)msec	83
1/T2*	0.073(0.017) 1/msec	83

Table 2 shows the correlation coefficients r and r^2

r(r^2)	T2*	1/T2*	BMD	W. Dens
S/I S	-0.43(0.18)	0.47(0.22)	0.68(0.47)	0.71(0.50)
A/P S	-0.63(0.40)	0.61(0.37)	0.90(0.80)	0.86(0.75)
M/L S	-0.78(0.60)	0.76(0.58)	0.94(0.88)	0.81(0.65)
S/I E	-0.44(0.19)	0.47(0.22)	0.61(0.37)	0.63(0.38)
S/I E	-0.64(0.40)	0.63(0.39)	0.79(0.62)	0.73(0.53)
S/I E	-0.66(0.44)	0.69(0.47)	0.89(0.80)	0.75(0.57)

In addition, wet density was correlated negatively with T2* (r=-0.732) and BMD was correlated negatively with T2* (r=-0.722).

DISCUSSION:

Clinically available methods used to assess fracture risk in patients with bone loss usually focus on bone density of some sort as an indicator of bone strength. The data we have collected shows that clinical measures available at this time predict bone strength in some directions better than others. In addition, bone strength predictions can be very good (r=0.94) for DXA measurement when the bone thickness is known, and when there are no soft tissue artifacts. T2* predictions of elastic modulus and strength are nearly as good as artifact-free BMD.

The fact that better correlation coefficients were usually found when transverse elastic moduli and ultimate strength were correlated with DXA and T2* measurements. is curious and will be further studied.

REFERENCES: 1) Goulet et al , J. Biomech. 27:375-389 2) Keller, J. Biomech. 27:1159-1168